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Design and Analysis of Embedded Antennas for 60-mm Mortars

by G. Katulka, R. Hall, B. Topper, and N. Hundley

ARL-TR-4483 **June 2008**

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2008

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
March 2006–June 2006

4. TITLE AND SUBTITLE
Design and Analysis of Embedded Antennas for 60-mm Mortars

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
G. Katulka, R. Hall, B. Topper,* and N. Hundley†

5d. PROJECT NUMBER
AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-BA
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-4483

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
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†Dynamic Science, Inc., 8433 N. Black Canyon Hwy., Phoenix, AZ 85021

14. ABSTRACT
The Defense Advanced Research Projects Agency and the U.S. Army are engaged in a high-risk/high-payoff project for the development of precision-guided 60-mm mortars in support of the Optically Designated Attack Munition program. This report describes the antenna design and performance characteristics required for an embedded telemetry-based onboard diagnostic system, which was conceived and developed at the U.S. Army Research Laboratory in support of experimental testing phases of the program. Our primary objective—to demonstrate rapid response and low-cost, reliable capability for projectile-mounted antennas compatible with commercially available telemetry products—was successfully achieved. Aspects of the specific design such as the antenna radiation pattern characteristics at the operating frequency of interest, the radio frequency tuning process of the antenna array, and the returned in-flight signal strength along the trajectory from the resultant diagnostic system are included and summarized in this report.

15. SUBJECT TERMS
antenna, embedded, mortar, telemetry, S-band, munitions

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			G. Katulka
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	20	19b. TELEPHONE NUMBER (*Include area code*) 410-306-1071

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures iv

Acknowledgments v

1. Introduction 1

2. Conclusions 7

3. References 8

Distribution List 9

List of Figures

Figure 1. Embedded antenna array shown with packaged telemetry electronics (left), and close-up view of single antenna element with machined radome cover (right). 2

Figure 2. Mini-Circuits RF combiner for integrating individual elements in the quad patch antenna array used to acquire telemetry during mortar flight testing. 3

Figure 3. Microwave return loss in decibels from a single antenna element hard mounted to the 60-mm mortar body. Shown is the return loss measurement taken directly from the mortar embedded antenna (blue) and the simulated return loss for a theoretical model approximation of the patch antenna (red). The difference in resonant frequency is accounted for by a slight geometrical difference between the actual patch antenna (to account for application of radome material during the hardware assembly process) and that of the theoretical model. 4

Figure 4. Experimentally measured radiation patterns for a circumferential embedded antenna array mounted on the 60-mm Optically Designated Attack Munition mortar body. All measurements are made at the S-band telemetry frequency of 2255 MHz inside the ARL anechoic chamber. Patterns are for the projectile roll (top) and pitch orientations (bottom)..5

Figure 5. Structural analysis results showing stress levels as a function of safety factor for the 60-mm mortar body. 6

Figure 6. Structural analysis results showing stress levels as a function of safety factor for the 60-mm mortar body. The highest stress levels observed were concentrated near the region between antenna patches designed to accommodate solar sensors, thus the machined solar sensor slots were omitted from the final design. 6

Figure 7. Signal strength received and recorded from the embedded quad patch antenna telemetry system for a prototype 60-mm mortar that was flight testing at ATC. 7

Acknowledgments

The authors acknowledge Barry Bolton from the U.S. Army Aberdeen Test Center for providing valuable engineering assistance during the flight testing phases of this effort. Additionally, David Hepner (U.S. Army Research Laboratory [ARL]) is acknowledged for valuable technical discussions and suggestions, and for providing motivation in completing this work. Dr. Stephen Weiss (ARL) is acknowledged for assistance with radiations patterns, and Thomas Harkins (ARL) is acknowledged for his thorough technical review of the final manuscript.

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1. Introduction

Theoretical simulations were carried out with a commercially available electromagnetic design software package, Microstripes from Flowmerics, Inc., (*1*) to determine the optimal patch locations within the 60-mm mortar body to achieve the desired radiation pattern having an omnidirectional shape coincident in the plane of the mortar body cross section. A circumferentially located antenna around the midbody of the mortar was selected since the forward section of the mortar was to be modified with guidance hardware to meet other objectives of the program (*2*). Thus the forebody could not be used to mount the typical fuze-type telemetry antenna. To save space around the perimeter of the mortar body, discrete patches were equally spaced at 90° intervals rather than a standard monolithic wraparound-style antenna utilized with many large-caliber projectiles of record (*3*, *4*). While a wraparound antenna should easily achieve the telemetry link margin and structural robustness for the 60-mm mortar, it would also discount the use of large amounts of surface area between the individual radiating antenna elements that could otherwise accommodate additional embedded sensors. Given the limited size of the 60-mm mortar, conserving surface area is a critical design consideration. Using standard radio frequency (RF) design techniques, an embedded quad patch was evaluated and selected for the 60-mm mortar. This design was also selected due to its ability to be rapidly implemented at a relatively low cost. The basic physical construct showing some of the individual antenna elements mounted on the mortar body is given in figure 1. The estimated material cost for the completed antenna from the U.S. Army Research Laboratory (ARL) is $38/individual patch element.

The antenna patches were fabricated from RT Duroid high-frequency laminate (RT6010) in the form of circular microstrip patches. This material is well known for its excellent RF properties, and it is widely used for military telemetry antennas (*5*). The antenna was modified to include a small tuning tab used for final resonant frequency tuning of the patches after mounting on the mortar body. A protective coating formed from two-part epoxy (JB Weld) was used as a radome covering on each of the four antenna elements (figure 1 shows installed antenna elements and radome). A miniature threaded RF connector (Coaxial Components Corp., 8M130SLG-1) was utilized to make all final connections from the technical manual package via flexible coaxial cable (Belden 1671A miniature RF coaxial cable) to the individual patches. This connector was selected because its quick-connect, threaded body enabled rapid assembly of the final instrumentation package thus expediting flight-testing schedules.

Coupling of the individual patches forming the quad antenna array was achieved with a commercial RF coupler, SDB-4-25, from Mini-Circuits shown in figure 2. Previous testing with these devices at ARL had demonstrated suitability for telemetry in the high-g environment of the 60-mm mortar of interest. The coupler's rated attenuation loss is –7dB, which was taken into

Figure 1. Embedded antenna array shown with packaged telemetry electronics (left), and close-up view of single antenna element with machined radome cover (right).

account in the link analysis at the S-band operating frequency of 2255 MHz, and the isolation between the coupled ports is a minimum of –22dB. The loss characteristic of an individual antenna element in the antenna array is provided in figure 3 where the microwave return loss in decibels measured with a Hewlett Packard 8753 Network Analyzer is compared to the simulated value. The measured frequency of the patch is 13.5 MHz higher compared to that of the simulated patch. The difference in frequency is because the patch as measured was intentionally modified from the theoretical model to increase its resonant frequency. This was done to compensate a resonant frequency drop of about 75 MHz, which was observed from the application of radome epoxy material to protect the individual antenna elements in flight. Final tuning of the patches is accomplished via tuning stub length adjustments made prior to radome epoxy application in order to achieve 2255 MHz. After the quad patch was completely assembled and tuned within the mortar body, the far-field radiation patterns were obtained.

These are provided in figure 4, showing the roll and the azimuthal or pitch radiation patterns, respectively. All measured radiation patterns were obtained at 2255-MHz resonant frequency in the anechoic chamber at ARL, Adelphi, MD.

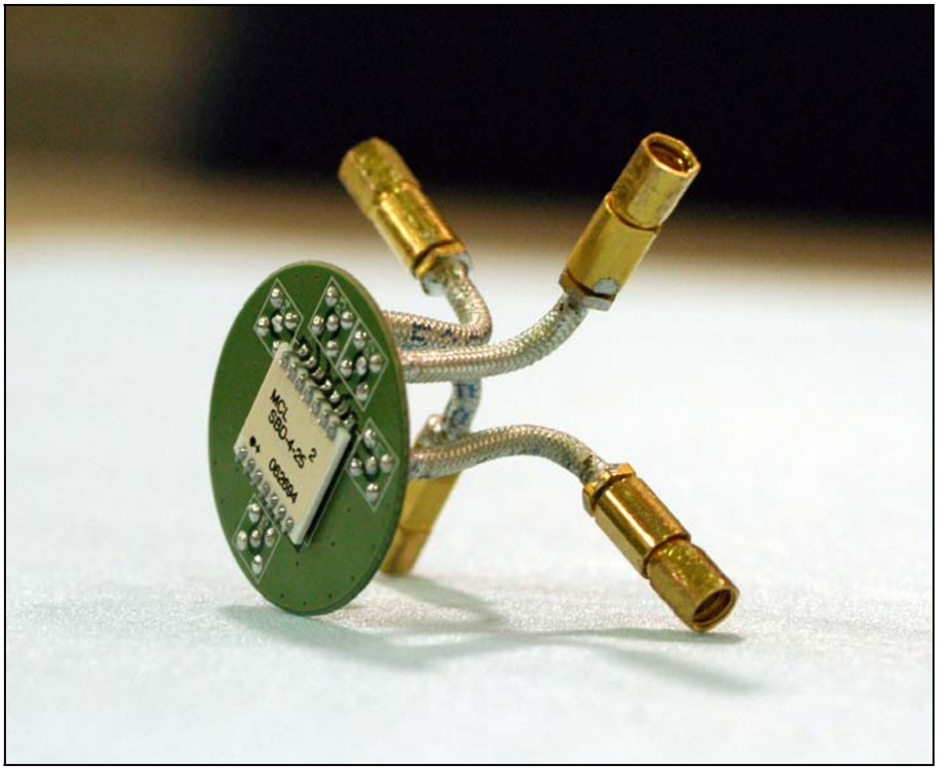
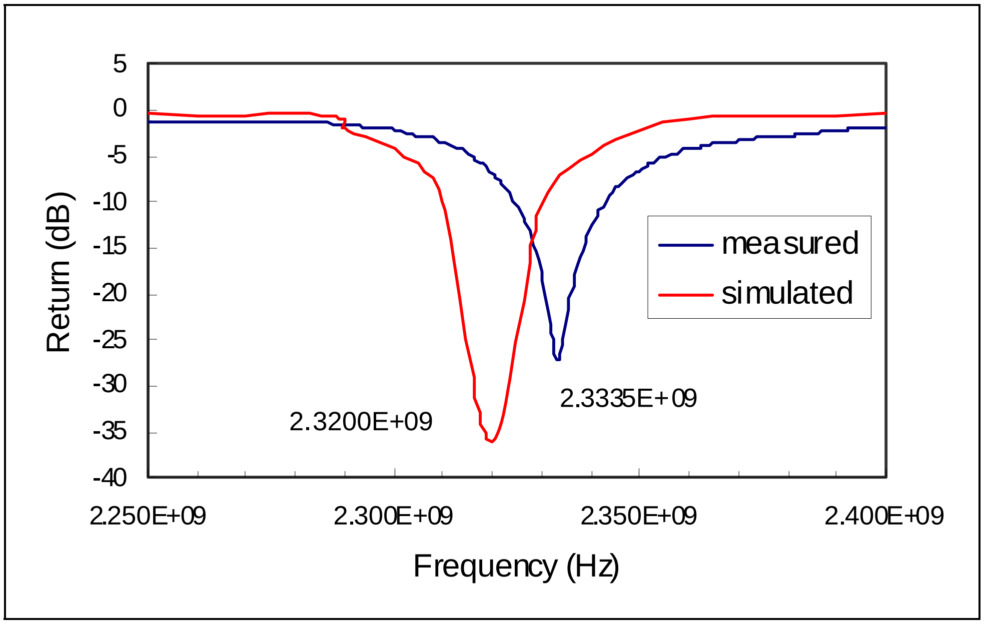


Figure 2. Mini-Circuits RF combiner for integrating individual elements in the quad patch antenna array used to acquire telemetry during mortar flight testing.

Structural simulations were carried out using commercial finite element analysis software from Algor, Inc. (*6*). This was done to verify the structural integrity of the mortar body as modified with embedded antenna recesses and to ensure that it would survive during projectile launch-induced body stresses. Results from these calculations are provided in figures 5 and 6. Input assumptions for the structural analysis included two static g-loading levels of 7000 and 10,000 g's. Structural survivability was experimentally verified prior to flight testing via laboratory shock table testing of a prototype 60-mm mortar having an embedded quad patch antenna.

Flight testing was conducted at the U.S. Army Aberdeen Test Center (ATC), Aberdeen Proving Ground, MD. Three prototype mortar rounds were shot to verify the reliability of the telemetry system (including the patch antenna array as designed) and the quality of the signal strength received from the mortars. Telemetry data for each of the three rounds were properly received as illustrated by the receiver automatic gain control data as shown in figure 7 for mortar round no. 19. This plot shows the receiver signal strength as a function of time from just before mortar launch (marked as muzzle exit in the plot) to ground impact at 28.6 s. The overall signal strength remains fairly constant throughout the mortar flight with anticipated signal undulations or oscillations coincident with the mortar spin rate. These are caused by the slightly asymmetric radiation pattern of the embedded antenna array as it spins about the mortar axis.



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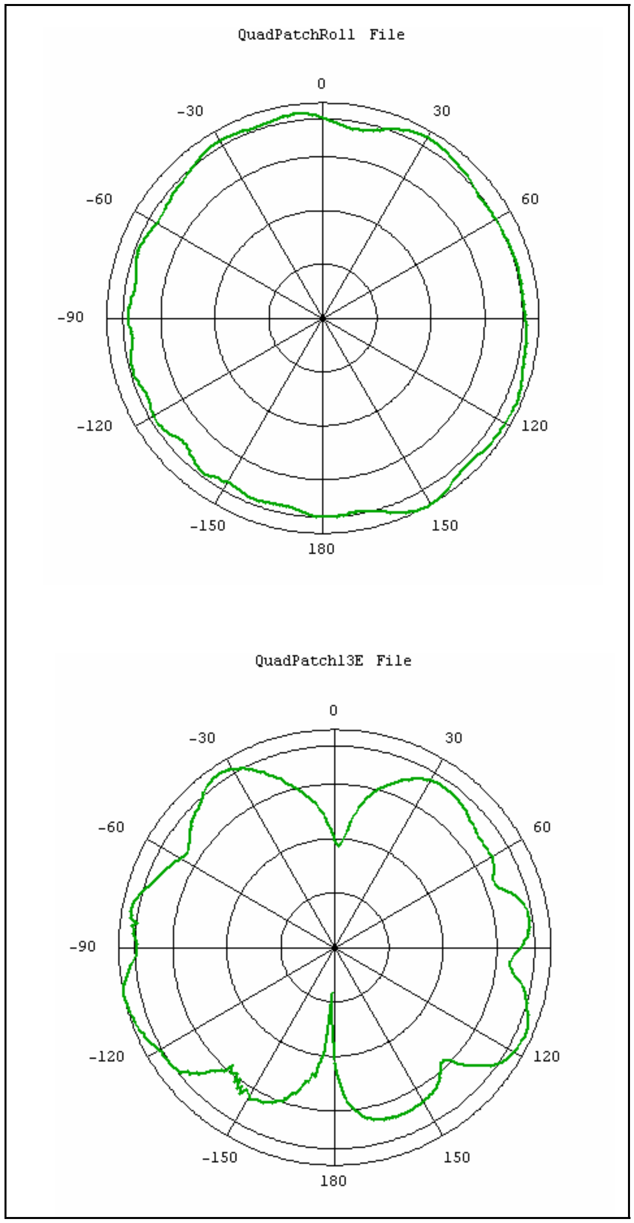

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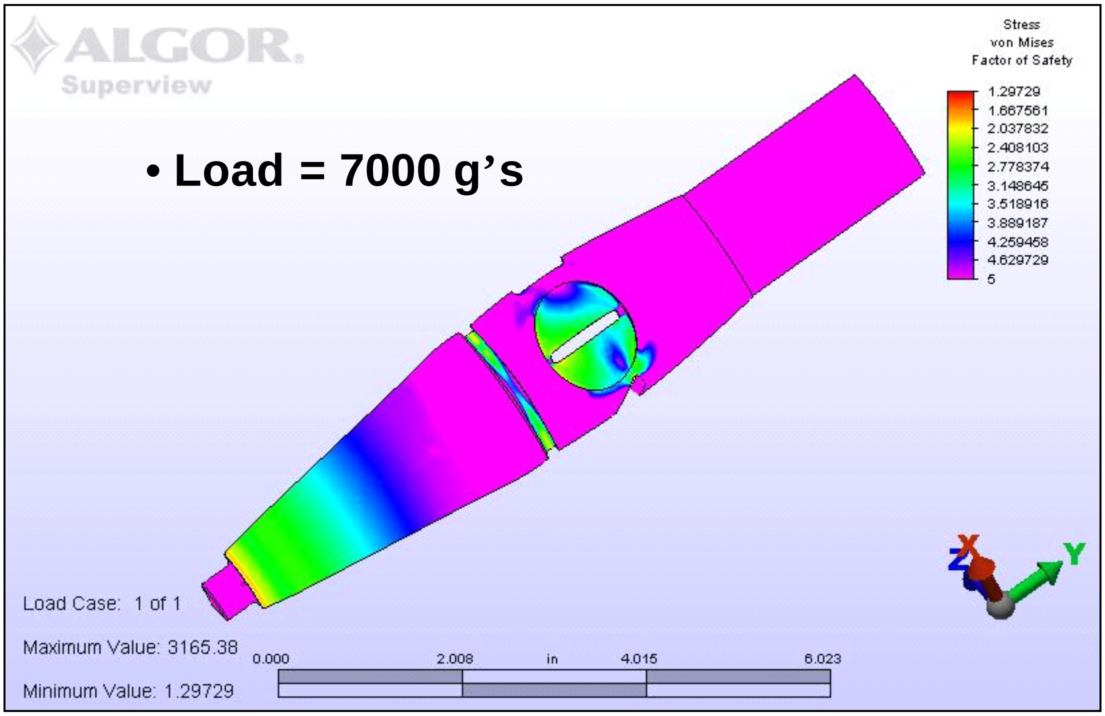

Figure 5. Structural analysis results showing stress levels as a function of safety factor for the 60-mm mortar body.

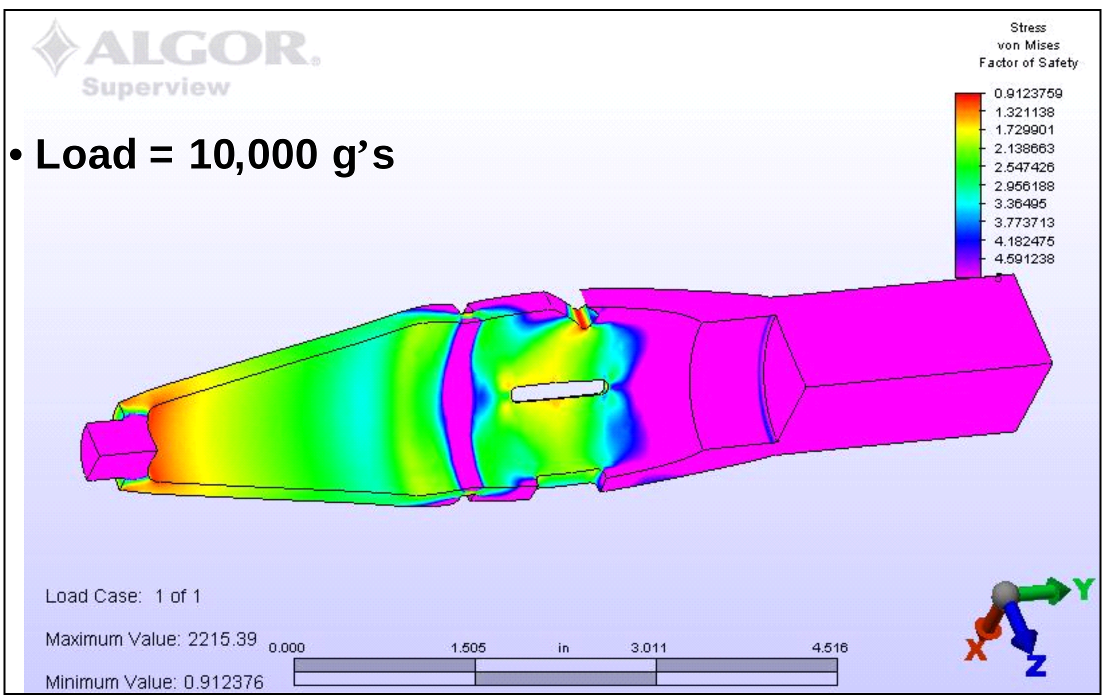

Figure 6. Structural analysis results showing stress levels as a function of safety factor for the 60-mm mortar body. The highest stress levels observed were concentrated near the region between antenna patches designed to accommodate solar sensors, thus the machined solar sensor slots were omitted from the final design.

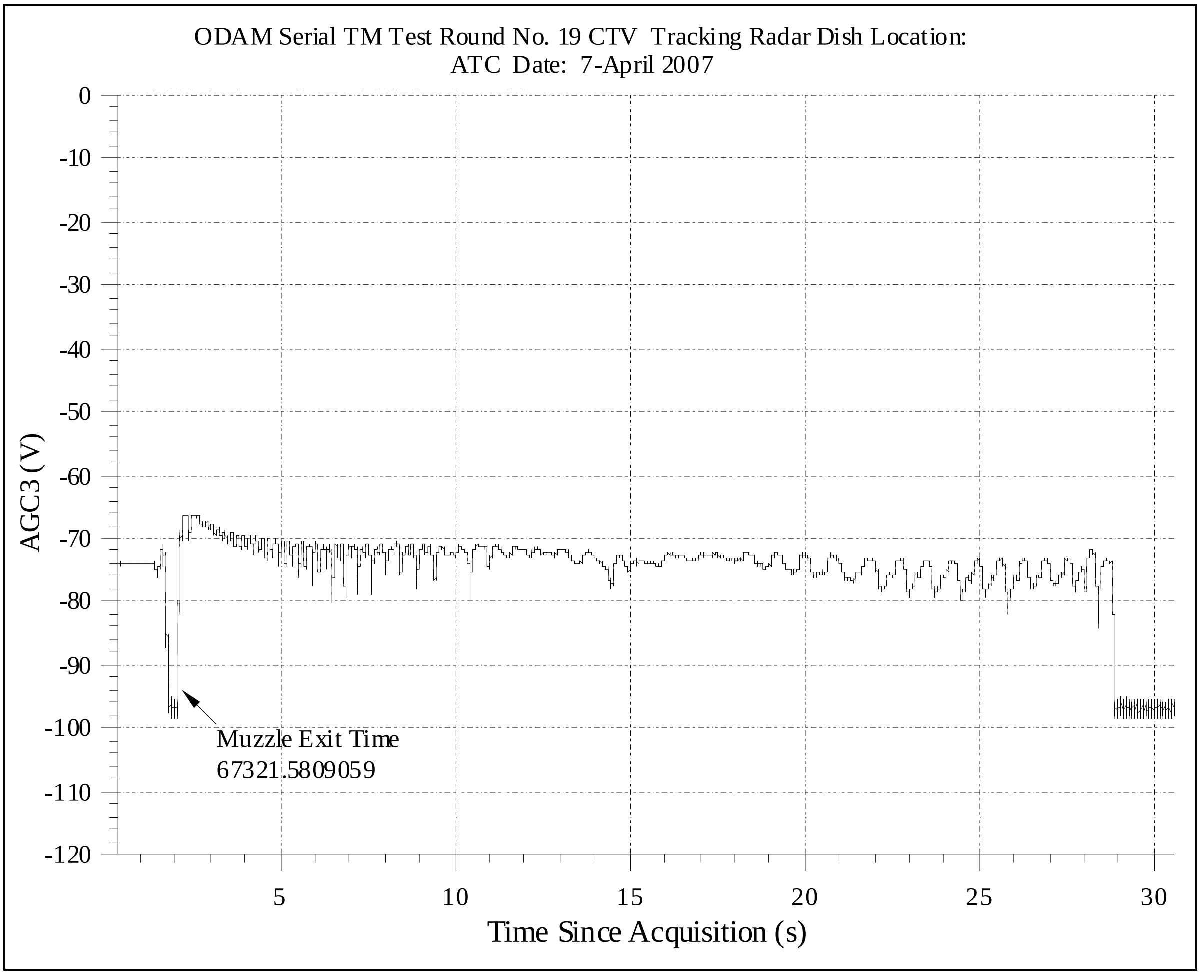

Figure 7. Signal strength received and recorded from the embedded quad patch antenna telemetry system for a prototype 60-mm mortar that was flight testing at ATC.

2. Conclusions

The design and performance characteristics of a low-cost antenna array embedded within a 60-mm mortar body were described in detail. The antenna is constructed from an array of patch antenna elements fabricated from standard microwave material and other low-cost commercial components modified to meet the requirements of a compact S-band telemetry system. Theoretical simulations of the antenna return loss characteristics used during the design phase were in close agreement with values measured directly from the embedded antenna, and minor resonant frequency discrepancies were accounted for. The antenna radiation pattern characteristics and the returned in-flight signal strength along a flight trajectory were also measured experimentally and demonstrated the viability of the approach as a low-cost, rapid-response alternative for embedded, high-g telemetry antenna designs.

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